

Radioactivity, Radionuclides & Radiation
8th Multimedia Training Course with Nuclides.net
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Presentation on Neutron Activation Analysis

Andrey Berlizov

Institute for Nuclear Research, Kyiv, Ukraine

Outline

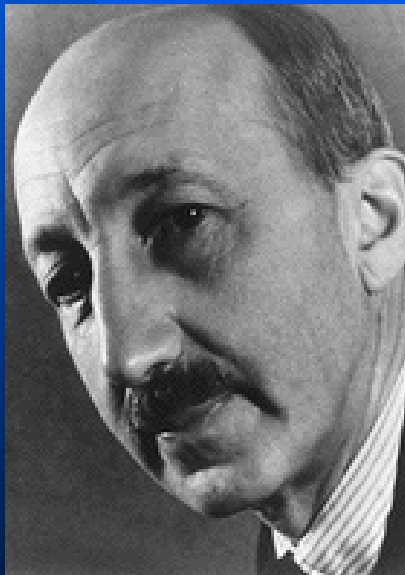
- Introduction to Neutron Activation Analysis
- Using Nuclides.net to solve simple activation problems
- NAAPRO – a versatile tool for predicting performance of NAA

Basics of Neutron Activation Analysis

- NAA is a sensitive analytical technique useful for performing both qualitative and quantitative multi-element analysis of major, minor, and trace elements in samples from almost every conceivable field of scientific or technical interest.
- NAA offers sensitivities that are superior to those attainable by other methods, on the order of parts per billion or better.
- Because of its accuracy and reliability, NAA is generally recognized as the "referee method" of choice.
- It is estimated that approximately 100,000 samples undergo NAA analysis each year.

Pioneers of Neutron Activation Analysis

- Neutron activation analysis was discovered in 1936 when Hevesy and Levi found that samples containing certain rare earth elements became highly radioactive after exposure to a source of neutrons.



George de Hevesy: 1885 - 1966.
The Nobel Prize in Chemistry 1943.



Hilde Levi: 1909 - 2003

The NAA method

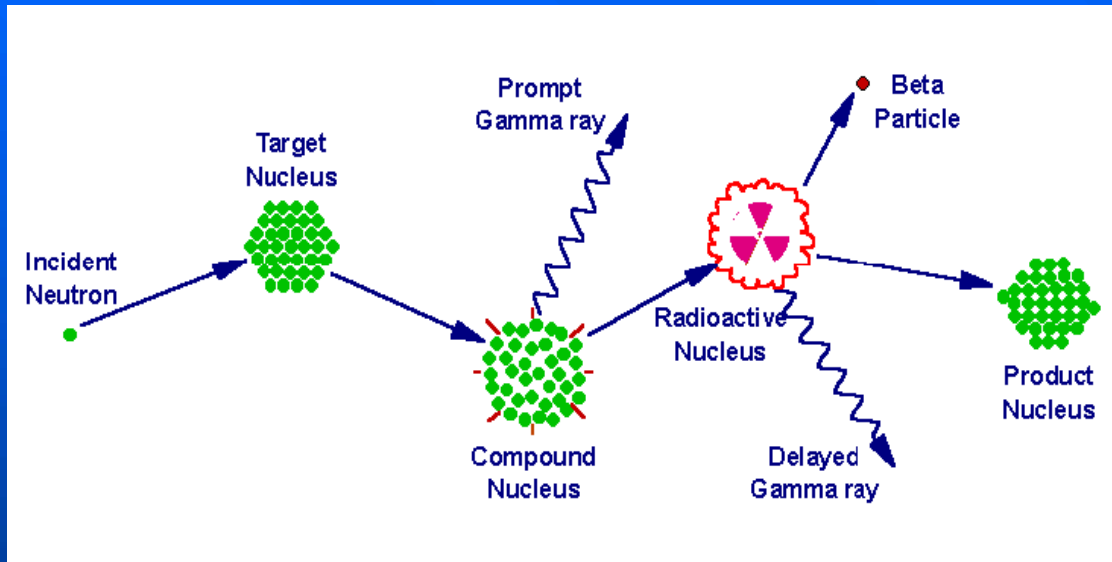


Diagram illustrating the process of neutron capture by a target nucleus followed by the emission of gamma rays.

*Pictures taken from Michael D. Glascock
University of Missouri Research Reactor (MURR)*

With respect to the time of measurement, NAA falls into two categories:

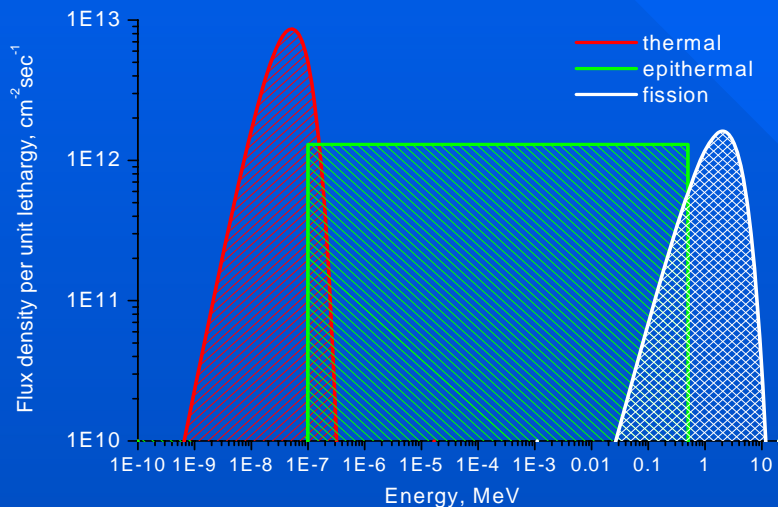
- prompt gamma-ray neutron activation analysis (PGNAA), where measurements take place during irradiation, or
- delayed gamma-ray neutron activation analysis (DGNA), where the measurements follow radioactive decay.

Reactor neutrons



10 MW water-water
nuclear research reactor

- **Thermal neutrons:** $E_n \leq 0.5$ eV. At room temperature, the energy spectrum of thermal neutrons is best described by a Maxwell-Boltzmann distribution with a mean energy of 0.025 eV and a most probable velocity of 2200 m/s.
- **Epithermal neutrons:** $0.5 \text{ eV} < E_n \leq 0.5 \text{ MeV}$. A Cd foil 1 mm thick absorbs all thermal neutrons but will allow epithermal and fast neutrons above 0.5 eV in energy to pass through. Typically the epithermal neutron flux represents about 2% of the total reactor neutron flux. **ENAA** – Epithermal Neutron Activation Analysis.



- **Fast (fission) neutrons:** $E_n > 0.5$ MeV. Induce nuclear reactions where the ejection of one or more nuclear particles - (n,p), (n,n'), and (n,2n) - are prevalent. Typically about 5% of the total reactor neutron flux consists of fast neutrons. **FNA** – Fast Neutron Activation Analysis.

Prompt NAA

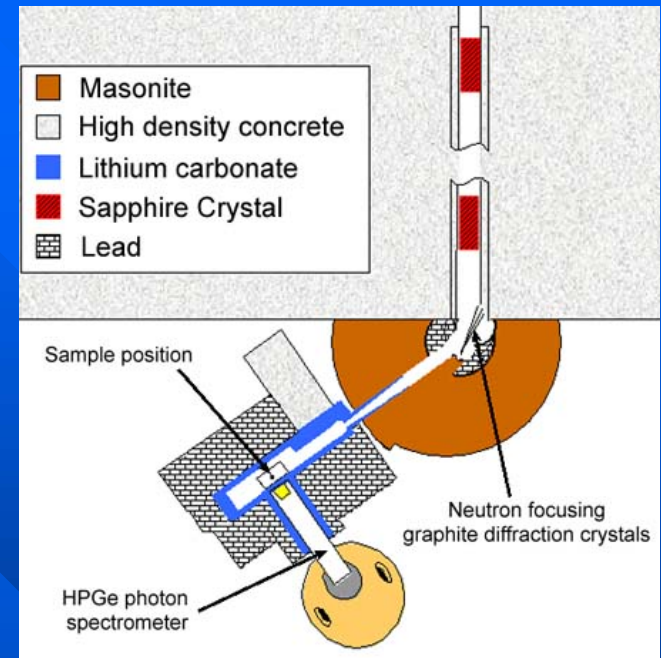
The **PGNAA** technique is generally performed by using a beam of neutrons extracted through a reactor beam port.

Utilization of the cold neutrons and chopped beams is more preferable for the better background conditions and highest sensitivity of the analysis.

The **PGNAA** technique is most applicable to elements:

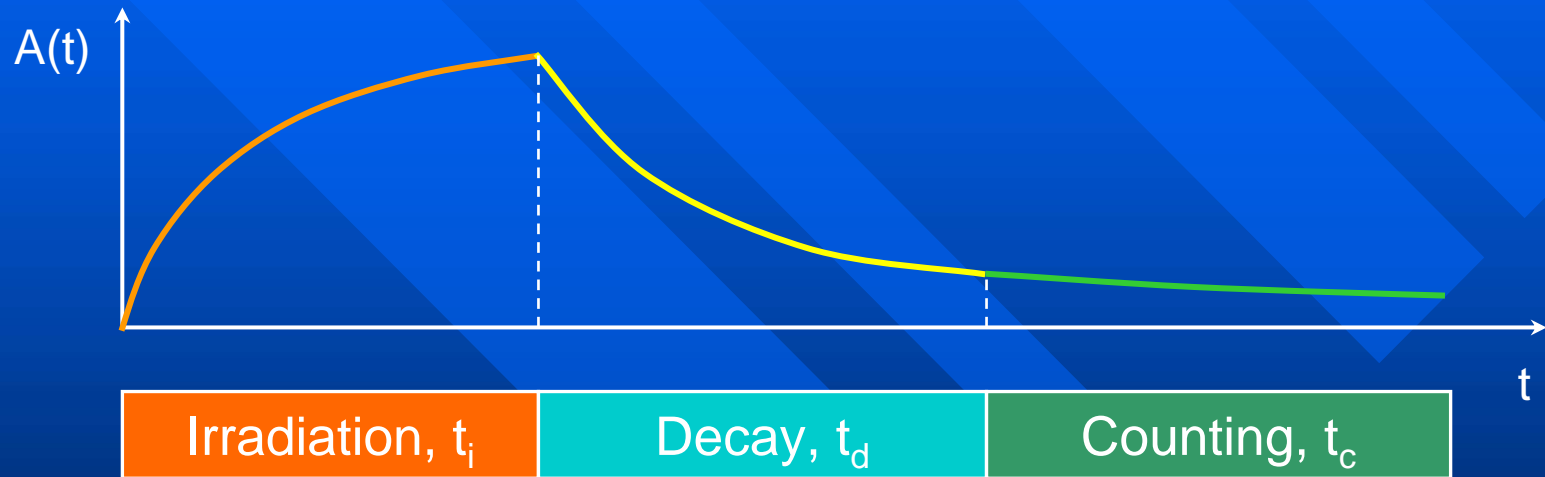
- with extremely high neutron capture cross-sections (B, Cd, Sm, and Gd);
- elements which decay too rapidly to be measured by DGNAA;
- elements that produce only stable isotopes;
- elements with weak decay gamma-ray intensities.

PGNAA facility at MIT



Delayed NAA (conventional NAA)

- The **DGNAA** technique is useful for the vast majority of elements that produce radioactive nuclides. It consists of the three principal steps:



- DGNAA is flexible with respect to time such that the sensitivity for a long-lived radionuclide that suffers from an interference by a shorter-lived radionuclide can be improved by waiting for the short-lived radionuclide to decay. This selectivity is a key advantage of DGNAA over other analytical methods.

Radiochemical vs. Instrumental NAA

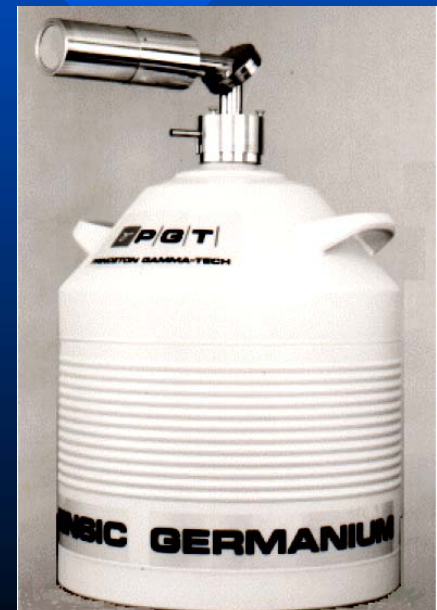
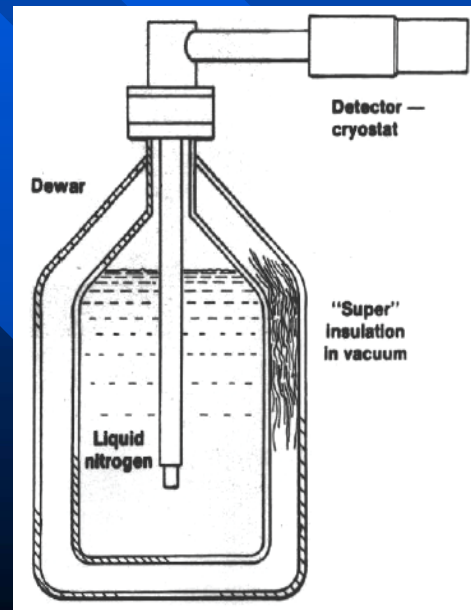
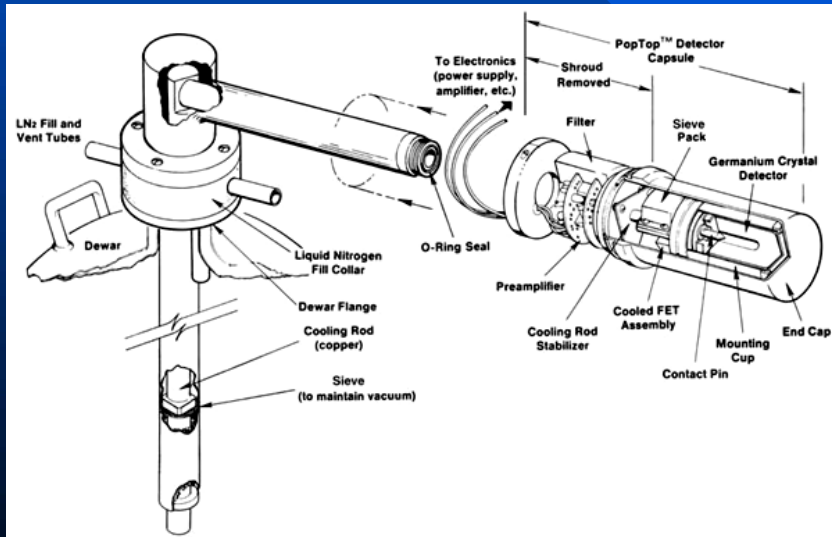
- The application of purely instrumental procedures is commonly called **Instrumental Neutron Activation Analysis (INAA)** and is one of NAA's most important advantages over other analytical techniques.
- If chemical separations are done to samples after irradiation to remove interferences or to concentrate the radioisotope of interest, the technique is called **Radiochemical Neutron Activation Analysis (RNAA)**. This technique is performed infrequently due to its high labor cost.

Ion exchange is a commonly used technique for post-irradiation sample treatment in RNAA



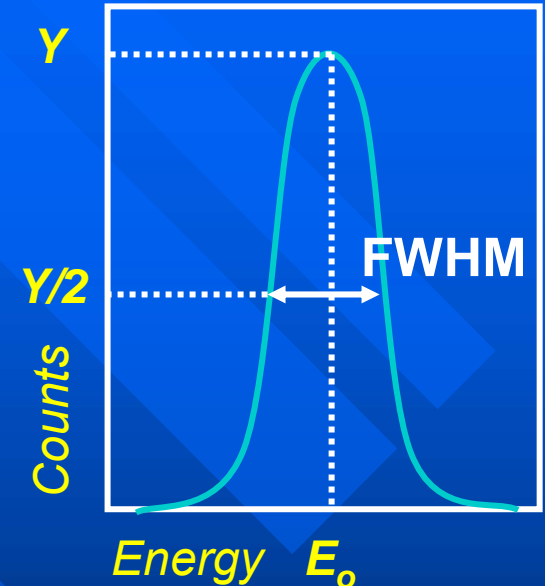
Measurement of Gamma Rays

- The instrumentation used to measure gamma rays from radioactive samples generally consists of a semiconductor detector, associated electronics, and a computer-based multi-channel analyzer.
- Hyperpure or intrinsic germanium (**HPGe**) detectors are commonly used. These detectors operate at liquid nitrogen temperatures (77 degrees K) by mounting the germanium crystal in a vacuum cryostat, thermally connected to a copper rod or "cold finger".



Important detector performance characteristics

- **Detector Resolution** is a measure of its ability to separate closely spaced Full Energy Peaks (FEP) in a spectrum. Detector resolution is specified in terms of the full width at half maximum (FWHM) of the 122-keV peak of Co-57 and the 1332-keV peak of Co-60.
- **Full Energy Peak Efficiency** is a measure of a detector ability to completely absorb the energy of a gamma ray.



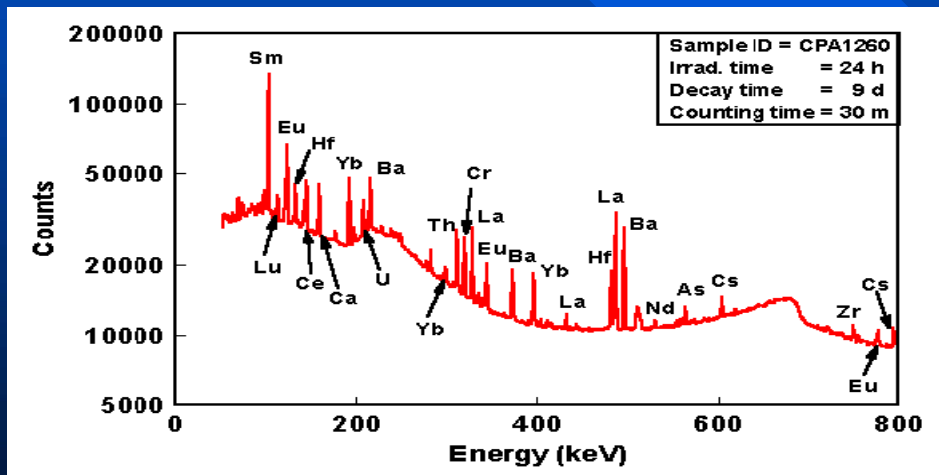
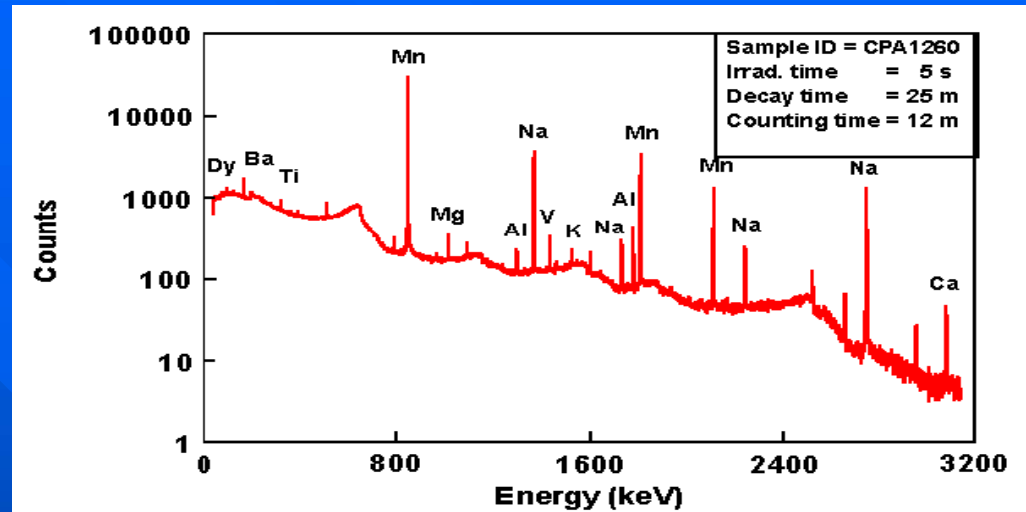
$$\text{FEP Efficiency} = \frac{\text{Number of counts in FEP}}{\text{Number of gamma rays emitted by a source}}$$

It is usually expressed in % relative to the value of $1.2 \cdot 10^{-3}$, which represents the efficiency of a 3-inch by 3-inch sodium iodide (NaI) detector for a Co-60 source (1332-keV gamma ray) at a distance of 25 cm from the crystal face.

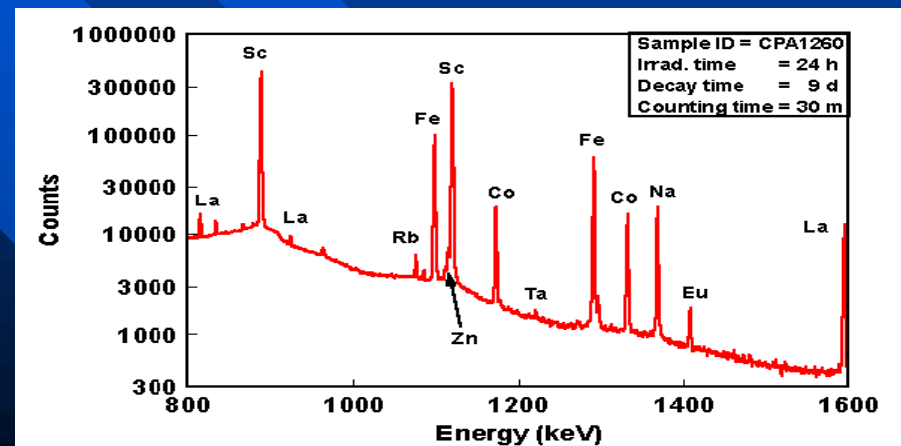
Typical gamma-ray spectra

(on the example of an irradiated pottery specimen)

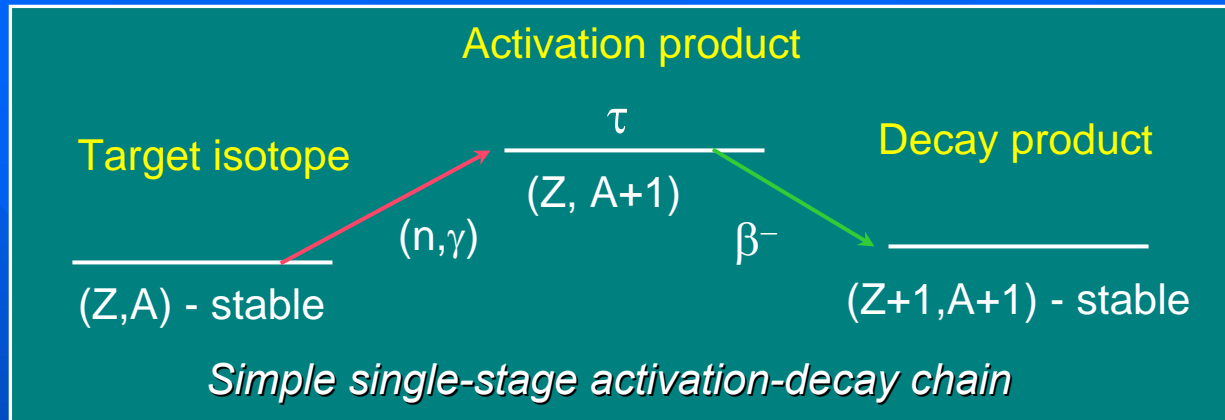
Short-term irradiation mode:
 $t_i = 5 \text{ s}$, $t_d = 25 \text{ m}$, $t_c = 12 \text{ m}$.



Long-term irradiation mode:
 $t_i = 24 \text{ h}$, $t_d = 9 \text{ d}$, $t_c = 30 \text{ m}$.



FEP Counts



FEP number of counts:

$$S = A_{\text{sat}} C_i C_d C_c \gamma \varepsilon(E_\gamma) t_c$$

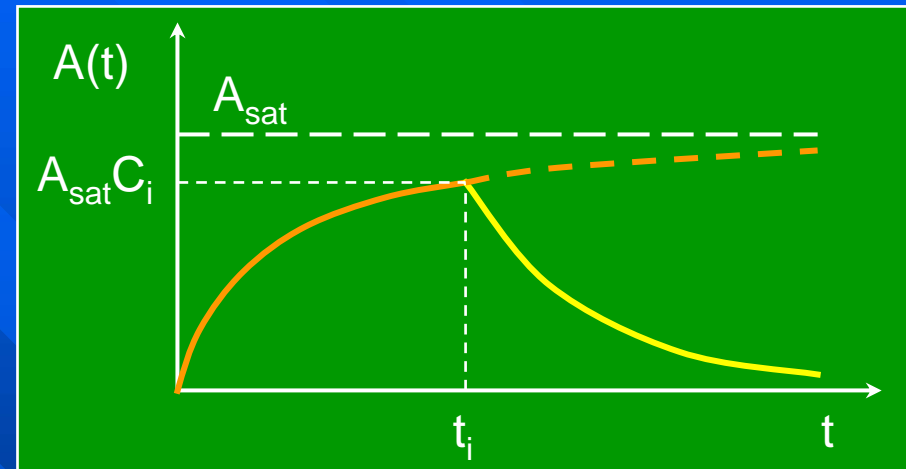
- A_{sat} – saturation activity;
- $C_i = 1 - \exp(-\lambda t_i)$, $C_d = \exp(-\lambda t_d)$ and $C_c = (1 - \exp(-\lambda t_c)) / \lambda t_c$ – corrections for a decay of an activation product during irradiation, decay and counting time intervals respectively;
- γ – gamma ray emission probability;
- $\varepsilon(E_\gamma)$ – FEP efficiency for energy E_γ ;
- t_i , t_d and t_c – irradiation, decay and counting time intervals respectively.

Calculating Element Concentration

$$A_{\text{sat}} = \frac{m f \rho N_A J}{M}$$

- m – sample mass, g;
- f – mass fraction of an element, g/g;
- ρ – abundance of a target isotope;
- N_A – Avogadro's number, mole⁻¹;
- J – neutron capture reaction rate, s⁻¹;
- M – atomic mass of an element, g/mole.

Illustration for the saturation activity



The procedure generally used to calculate concentration in the unknown sample is to irradiate the unknown sample and a comparator standard containing a known amount of the element of interest together in the reactor. The equation used to calculate the mass of an element in the unknown sample relative to the comparator standard is

$$f_x = f_{\text{std}} \frac{A_{\text{sat}}^x}{A_{\text{sat}}^{\text{std}}}$$

Simple Activation Problem: formulation

- **Problem:** A 200 mg soil sample is irradiated in a reactor for 5 min. Consider activation of Al, whose mass fraction in the sample is 4.7%. Calculate the saturation activity of an activation product, as well as its activity at the end of irradiation and on 30 min after the irradiation. Irradiating neutron flux: thermal neutrons – $\Phi_{th} = 5 \cdot 10^{10} \text{ cm}^{-2}\text{s}^{-1}$, epithermal neutrons – $\Phi_{epi} = 7 \cdot 10^8 \text{ cm}^{-2}\text{s}^{-1}$. Effective temperature of the thermal neutron flux $T_{eff} = 300 \text{ K}$.

$$A_{sat} = \frac{m f \rho N_A J}{M}$$

$$J = \Phi_{th} \cdot \sqrt{\frac{293.6}{T_{eff}}} \cdot \frac{\sqrt{\pi}}{2} \cdot \sigma_0 (2200 \text{ m/s}) + \Phi_{epi} \cdot I$$

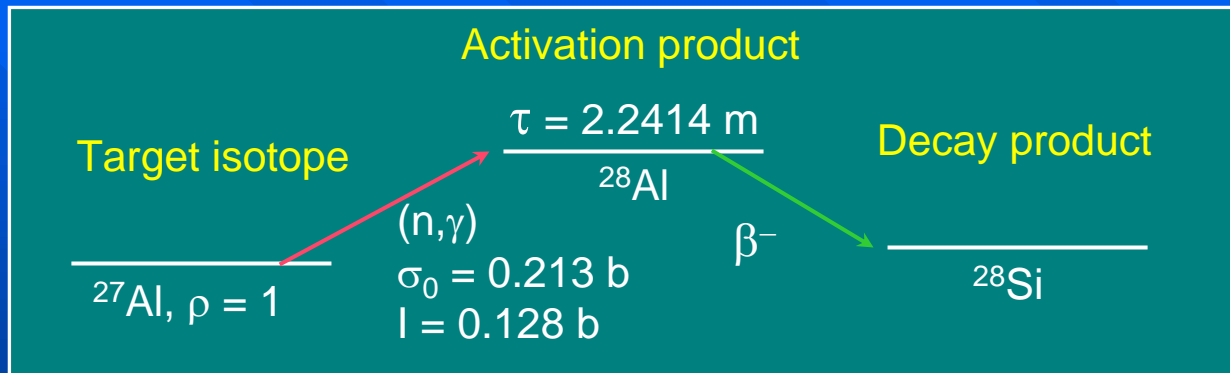
$$A(t_i) = A_{sat} \cdot C_i = A_{sat} \cdot (1 - \exp(-\lambda t_i))$$

$$A(t_i + t_d) = A(t_i) \cdot C_d = A(t_i) \cdot \exp(-\lambda t_d)$$

$$\lambda = \frac{\ln 2}{\tau}$$

Simple Activation Problem: solution

- Step #1: Using Nuclides Chart and DataSheet determine target isotope and its abundance, activation product and its half-live, decay product. Using X-section find cross-section at 2200 m/s and resonance integral for the neutron capture reaction on the target isotope.



- Step #2: Calculate reaction rate:

$$J = 5 \cdot 10^{10} \cdot \sqrt{\frac{293.6}{300}} \cdot \frac{\sqrt{\pi}}{2} \cdot 0.213 \cdot 10^{-24} + 7 \cdot 10^8 \cdot 0.128 \cdot 10^{-24} = 0.9427 \cdot 10^{-14} \text{ s}^{-1}$$

- Step #3: Calculate activities:

$$A_{\text{sat}} = \frac{0.2 \cdot 0.047 \cdot 1.0 \cdot 6.02 \cdot 10^{23} \cdot 0.9427 \cdot 10^{-14}}{26.982} = 1.977 \text{ MBq}$$

$$A(5 \text{ m}) = 1.977 \cdot (1 - \exp(-\frac{0.693 \cdot 5}{2.2414})) = 1.556 \text{ MBq}$$

$$A(35 \text{ m}) = 1.556 \cdot \exp(-\frac{0.693 \cdot 30}{2.2414}) = 145.8 \text{ Bq}$$

NAAPRO – a program for Neutron Activation Analysis Prognosis and Optimization

MARC-VI – Methods and Applications of Radioanalytical Chemistry, Kailua Kona, USA, April 2003

MTAA-11 – Modern Trends in Activation Analysis, Guildford, UK, June 2004

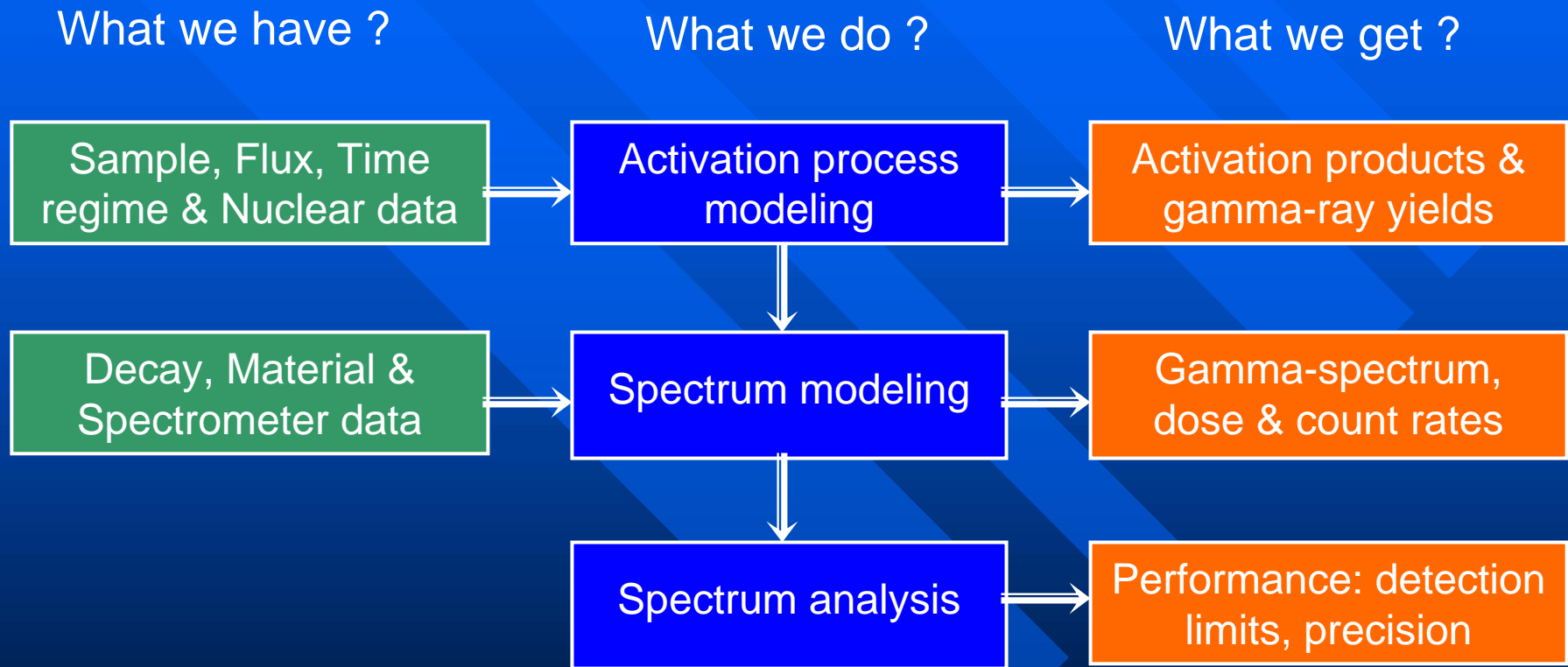
V.K. Basenko, A.N. Berlizov, I.A. Malyuk, V.V. Tryshyn, NAAPRO: A Code for Predicting Results and Performance of Neutron Activation Analysis, JRNC, Vol.263, No.3 (2005) pp. 675-681.

A.N. Berlizov, V.K. Basenko, R.H. Filby, I.A. Malyuk, V.V. Tryshyn, NAAPRO Detector Model, a Versatile and Efficient Approach to Gamma-Ray Spectrum Simulation, NIM A, 562 (2006) pp. 245-253.

V.K. Basenko, A.N. Berlizov, R.H. Filby, I.A. Malyuk, V.V. Tryshyn, Current Status and Prospects of Development of the NAAPRO Code, JRNC, Vol. 271, No. 2, 2007 (in press)

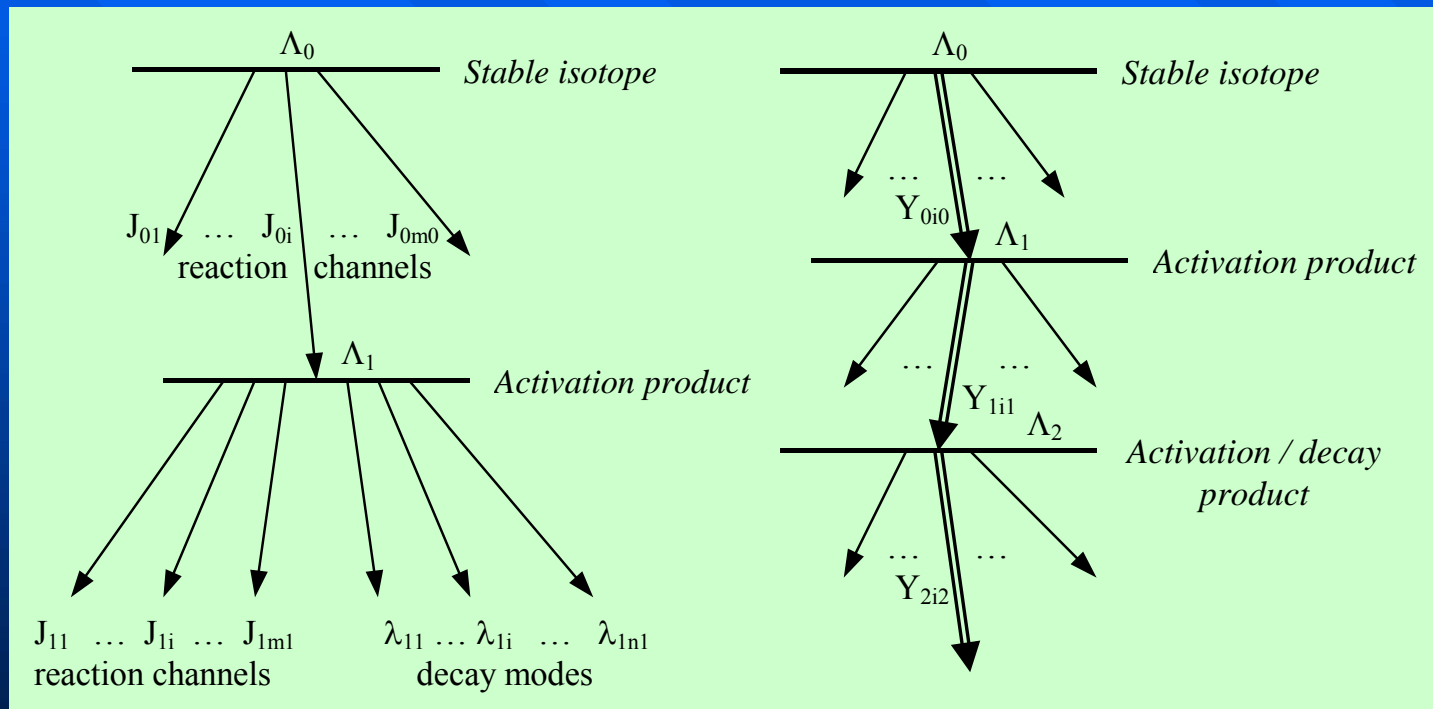
July 2004 – a Version 01.beta became available through RSICC (ORNL, <http://www-rsicc.ornl.gov/>) and OECD/NEA databank (Paris, <http://www.nea.fr/html/dbprog/>)

NAAPRO approach



Activation process modeling

A general case of activation of stable isotopes of a chemical element was considered. A Cauchy problem for generalized nuclear transformation tree has been solved.



(a) – nuclear transformation tree at activation, (b) – selected nuclear transformation chain $c = \{i_0, i_1, \dots, i_{Nc-1}\}$. Λ_i and Y_{ij} are generalized decay constant and branching coefficient respectively.

Activation process modeling: expressions

The probability of creation of the i -th radionuclide per nucleus of the element under the neutron exposure during irradiation time interval t_1 and its decay within the measurement time interval t_3 following cooling period t_2 :

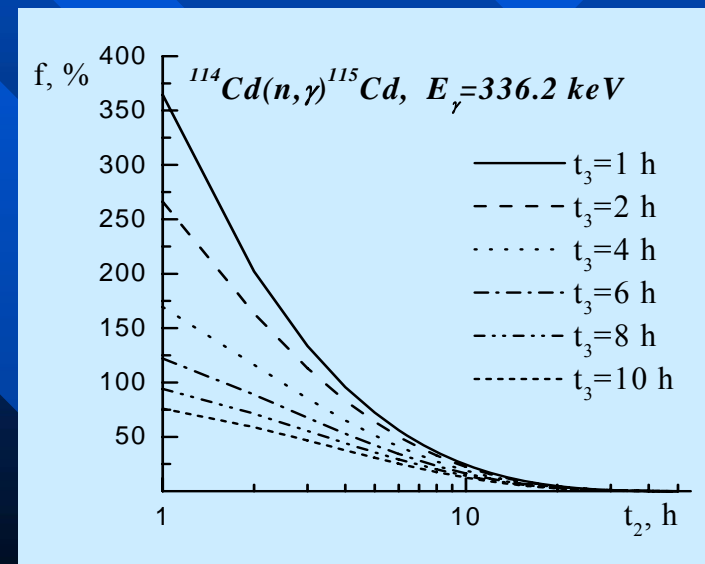
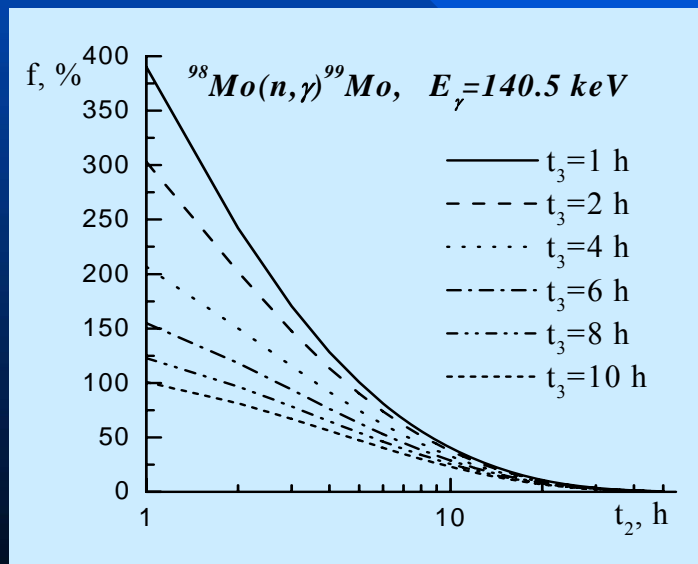
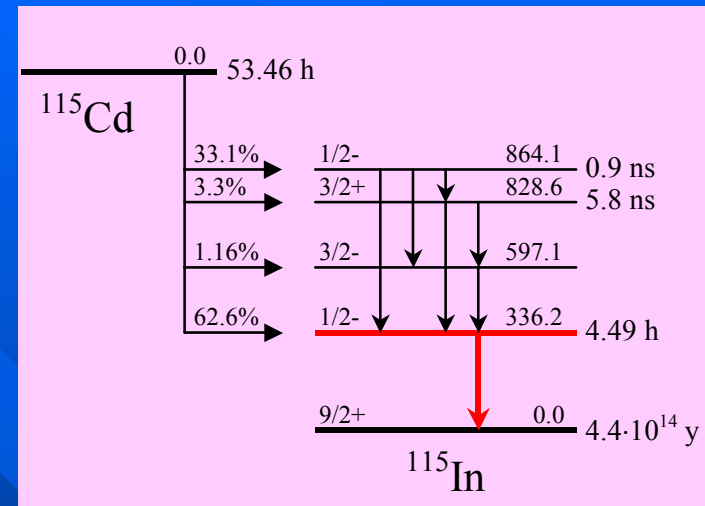
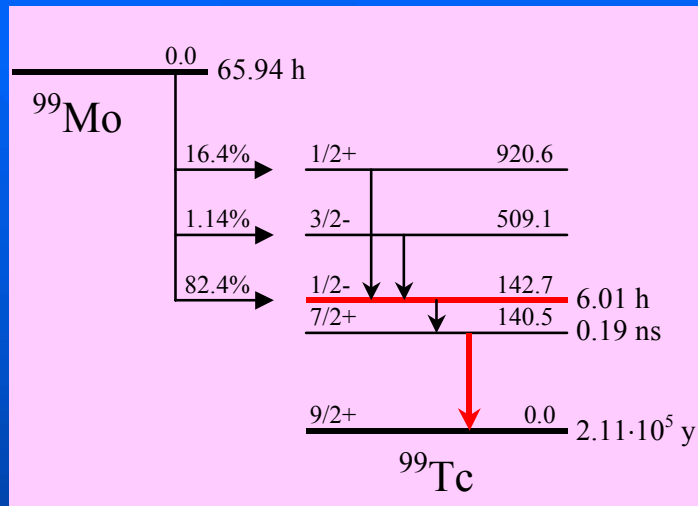
$$P_i = \sum_{n=1}^{N_{st}} \rho_n p_i^n = \sum_{n=1}^{N_{st}} \rho_n \sum_c p_{ic}^n$$

N_{st} – number of stable isotopes of the element considered, ρ_n – abundance of n -th stable isotope; p_{ic}^n – probability reduced per nucleus of the n -th stable isotope and per activation chain 'c':

$$p_{ic}^n = \lambda_i^n \left(\prod_{k=0}^{i-1} A_k^n Y_{kc_k}^n \right) \sum_{j=N}^i \frac{\exp(-\lambda_j^n t_2)}{\lambda_j^n} \left(1 - \exp(-\lambda_j^n t_3) \right) \sum_{m=N}^j \frac{D_m^{-1}}{\prod_{\substack{k=m \\ k \neq j}}^i (\lambda_k^n - \lambda_j^n)} \sum_{l=0}^m \frac{\exp(-\lambda_l^n t_1)}{\prod_{\substack{k=0 \\ k \neq l}}^m (A_k^n - A_l^n)}$$

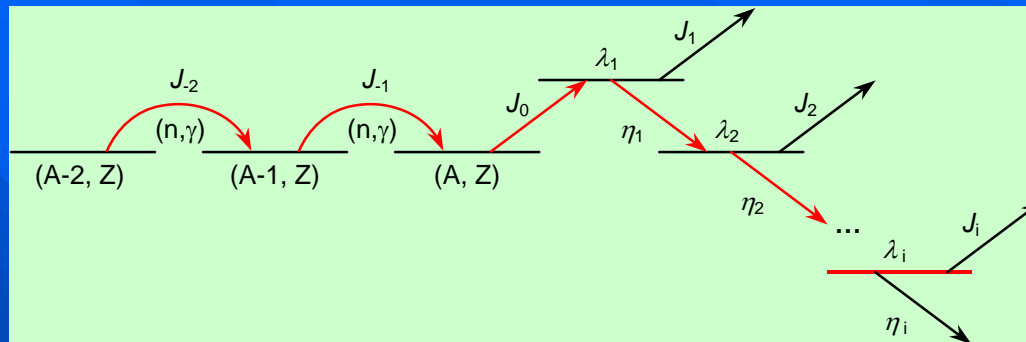
D_m – decontamination factors (RNAA).

Activation process modeling: example #1



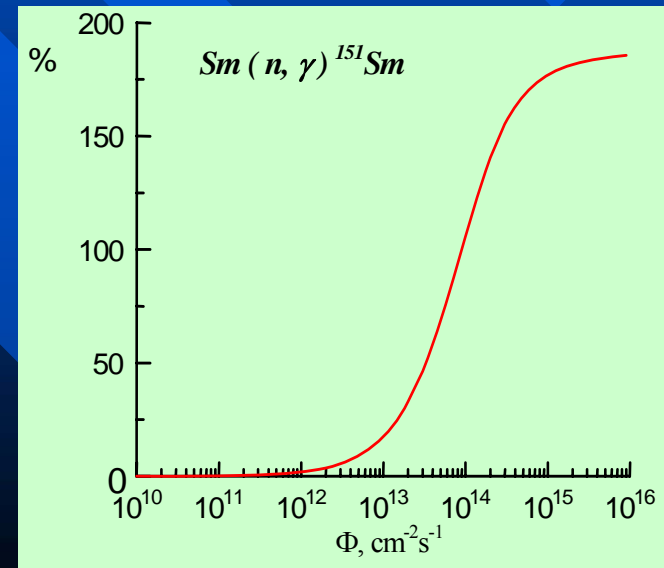
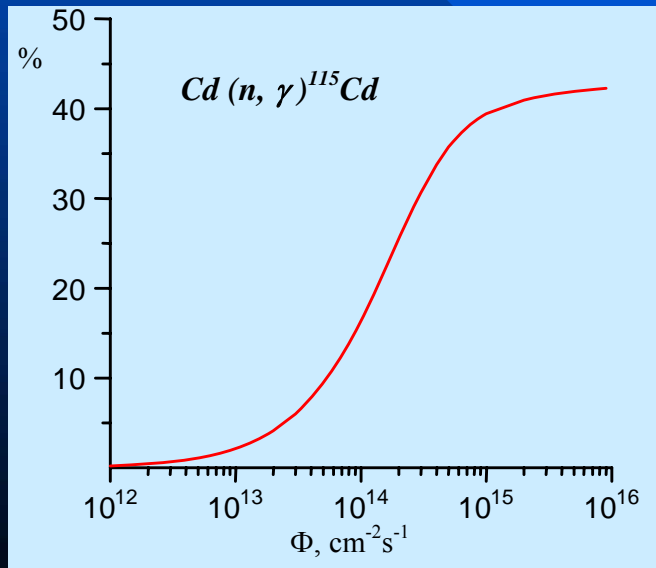
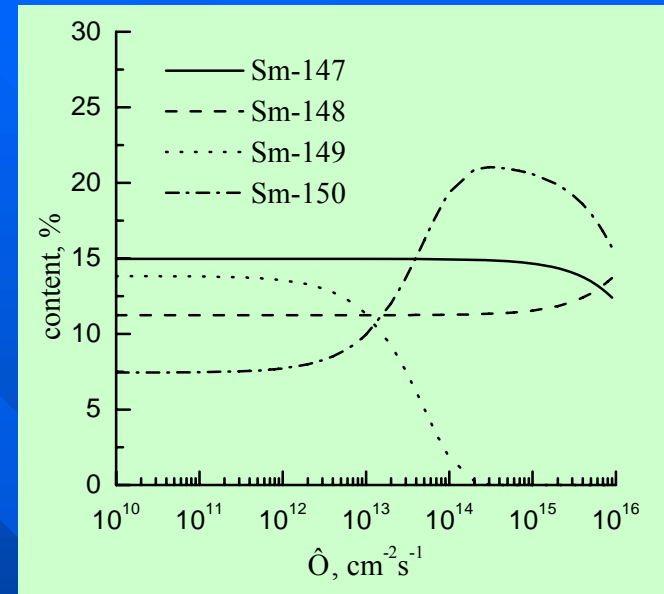
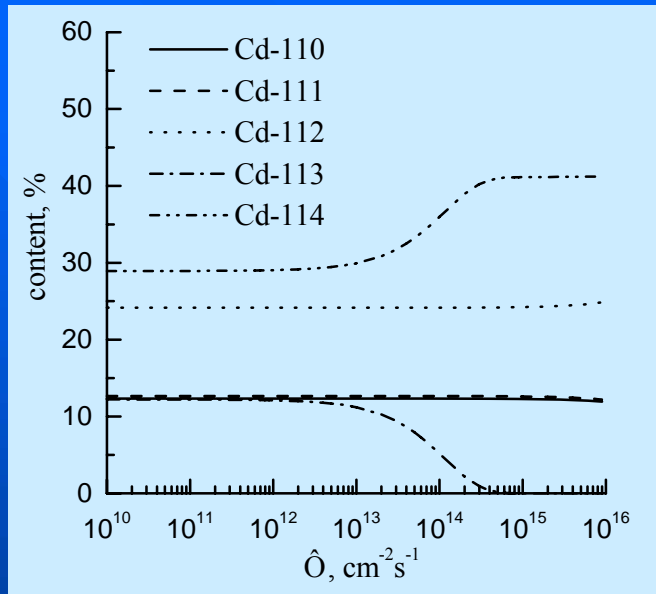
Activation process modeling: example #2

Burnup of stable isotopes:



Isotope	Content, %	Reaction	Product	$T_{1/2}$, day	σ , barn
Cd-110	12.32	(n, γ)	Cd-111	stable	10.0
Cd-111	12.67	(n, γ)	Cd-112	stable	21.7
Cd-112	24.15	(n, γ)	Cd-113	stable	2.1
Cd-113	12.21	(n, γ)	Cd-114	stable	23977.3
Cd-114	28.93	(n, γ)	Cd-115	2.2275	0.51
Sm-147	14.97	(n, γ)	Sm-148	stable	58.1
Sm-148	11.24	(n, γ)	Sm-149	stable	2.4
Sm-149	13.83	(n, γ)	Sm-150	stable	55887
Sm-150	7.44	(n, γ)	Sm-151	32850	95.7

Activation process modeling: example #2



NAAPRO Nuclear Data Library

- Radionuclide library is based on the Evaluated Nuclear Structure Data File, appended by the KX- and LX-ray data and 511 keV photon intensities.
- Photon interaction data are taken from EPDL data library.
- Continuous and fixed (14 MeV) energy neutron cross-section libraries were built using the following data sources, arranged according to the assigned priorities:

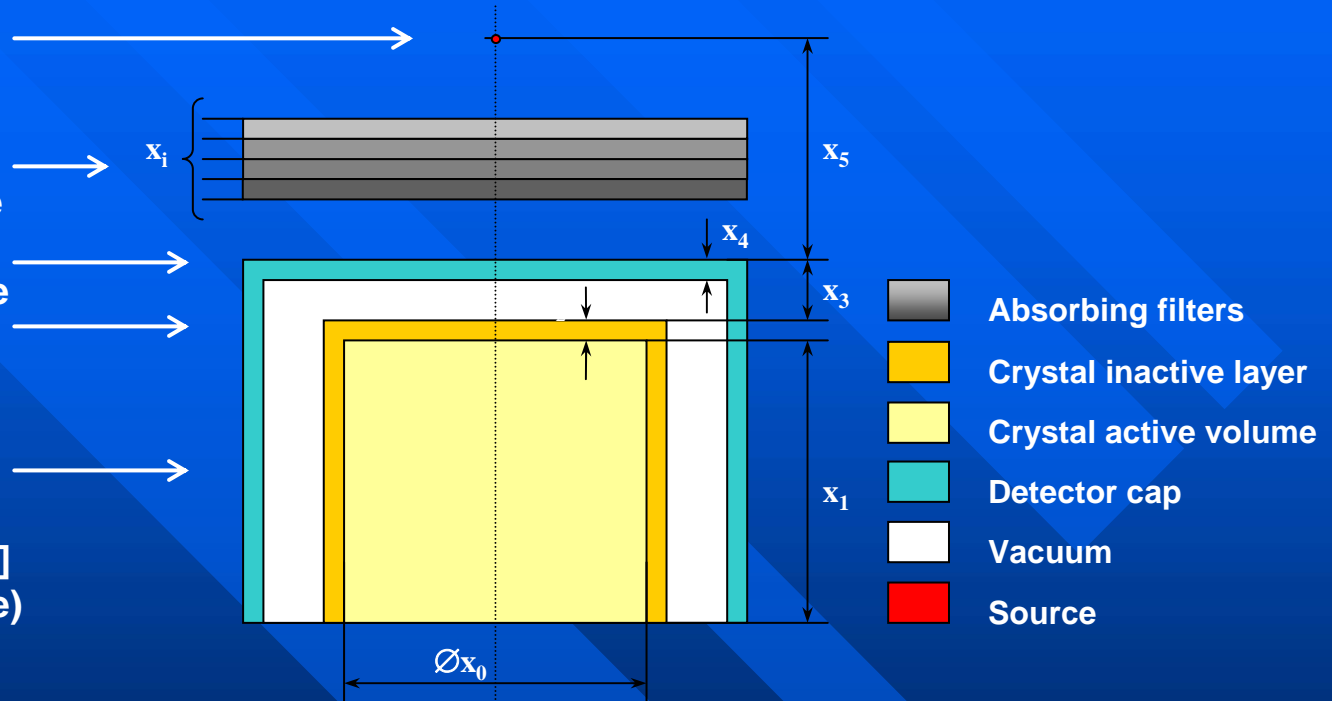
Data Library	Origin
EAF-4 – European Activation File	Energy research Center of the Netherlands, Petten, 1995
RNAL – Reference Neutron Activation Library	Nuclear Data Section, International Atomic Energy Agency, 2000
ENDF/B-VI Release 8 – Evaluated Nuclear Data File	Brookhaven National Laboratory, National Nuclear Data Center, USA, 2001
JENDL-3.2 – Japanese Evaluated Nuclear Data Library	Nuclear Data Center of Japan Atomic Energy Research Institute and Japanese Nuclear Data Committee, Japan, 1994
JEF-2.2 - Joint Evaluated File	European Library, NEA, 1992
BROND-2 –Russian Evaluated Neutron Reaction Data Library	Institute of Physics and Power Engineering, Obninsk, Russian Federation, 1994
CENDL-2 – Chinese Evaluated Nuclear Data Library	Chinese Nuclear Data Center, Institute of Atomic Energy, China, 1995
ADL-3 – Activation Data Library	Institute of Physics and Power Engineering, Obninsk, Russian Federation, 1994

Spectrum modeling: detector model

Arbitrary source to
detector distance

Up to 10 absorbing
layers in addition to the
detector input window
and inactive layer of the
crystal.

Arbitrary crystal
material: Ge, NaI, BGO;
and dimensions:
 x_0 & $x_1 = [3 \text{ cm}, 10 \text{ cm}]$
(4 – 250 % rel. eff. HPGe)



Detector response function:

$$G(E, E_i) = \varepsilon_{\text{tot}}(E_i) \cdot \{ \omega_{\text{FE}}(E_i) \cdot g_p(E, E_i) + \omega_{\text{SE}}(E_i) \cdot g_p(E, E_i - m_0 c^2) + \omega_{\text{DE}}(E_i) \cdot g_p(E, E_i - 2m_0 c^2) + (1 - \omega_{\text{FE}}(E_i) - \omega_{\text{SE}}(E_i) - \omega_{\text{DE}}(E_i)) \cdot (g_c(E, E_i) + k_{\text{BS}} \cdot g_{\text{BS}}(E, E_i)) \}$$

Spectrum modeling: detector efficiency

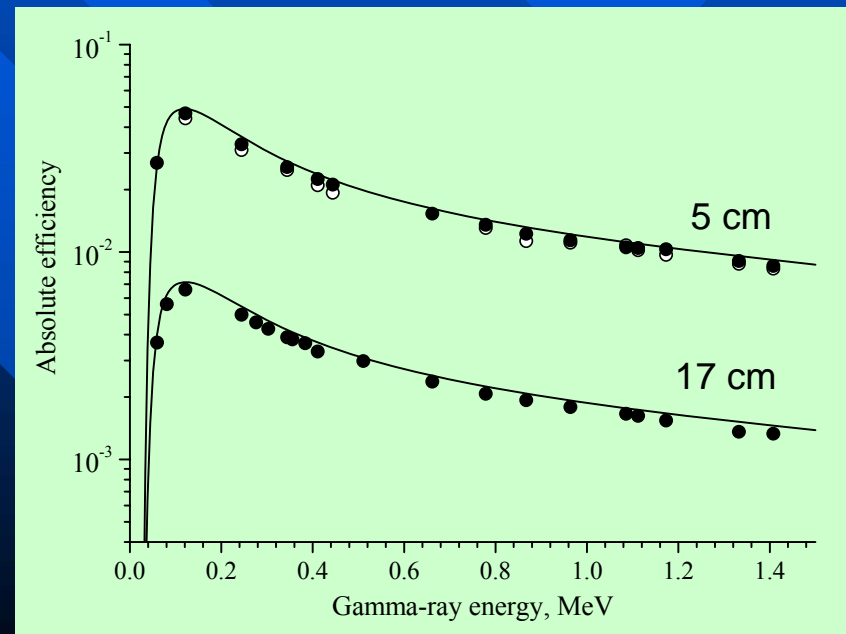
- Total efficiency - numerical integration over the detector sensitive volume:

$$\epsilon_{\text{tot}} = \frac{1}{2} \left\{ \int_{\eta_1}^1 [1 - \exp(-\mu_c H/t)] \cdot \exp(-\mu_a x_a/t) \cdot dt + \int_{\eta_2}^{\eta_1} \left[1 - \exp(\mu_c L/t - \mu_c R/\sqrt{1-t^2}) \right] \cdot \exp(-\mu_a x_a/t) \cdot dt \right\}$$

- Photofraction & SE and DE peak to total ratios – MCNP calculations for a bare crystal in the range 3 – 10 cm both for height and diameter with 1×1 cm² mesh, energy range from 5 keV to 4000 keV, and source to crystal distances – 0 cm, 4 cm, and 10 cm.

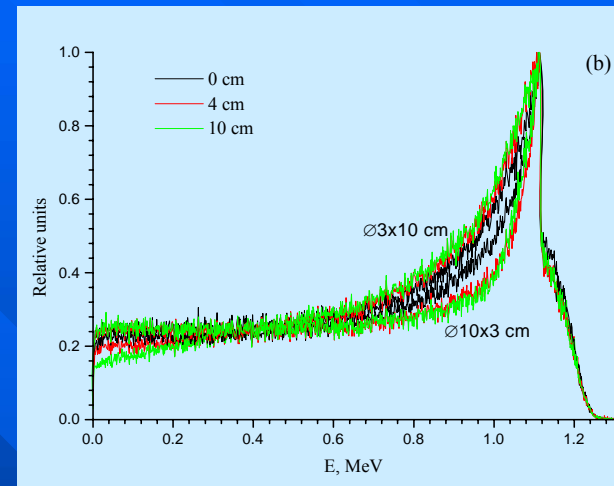
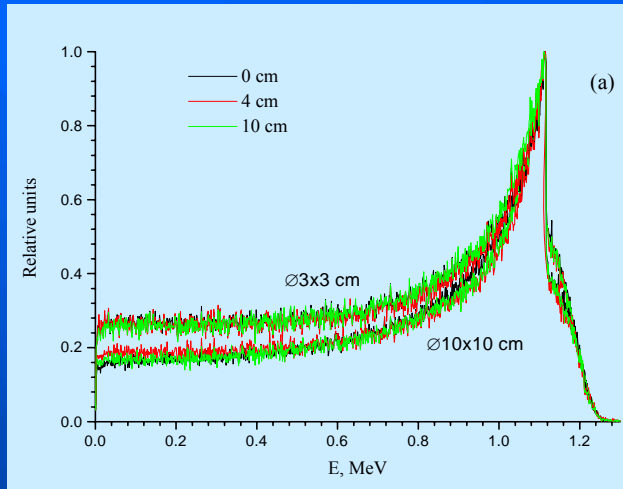
- Example:

detector – coaxial 60% HPGe;
model – GC6020 (Canberra);
crystal dimensions – Ø74×53 mm;
inactive Ge – 0.07 cm;
detector end cap – 0.15 cm Al;
detector end cap to crystal – 0.5 cm.

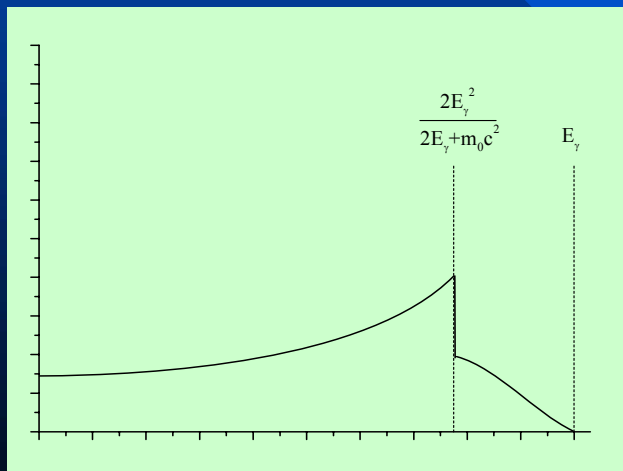


Spectrum modeling: Compton continuum

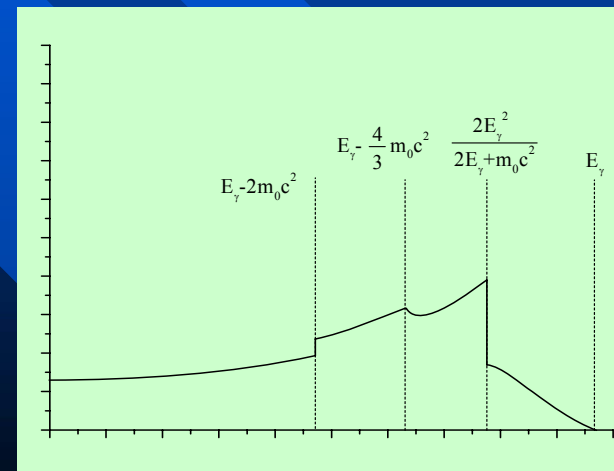
Testing Compton continuum shapes:



Regions of Compton continuum parameterization:



$E_\gamma \leq 1022$ keV



$E_\gamma > 1022$ keV

Spectrum modeling: g_{BS} & background

- Backscatter peak shape function:

$$g_{BS}(E', E) = \frac{1}{N} \int_{E_{min}}^E g_P(E', E'') \cdot \sigma_c(E - E'', E) \cdot \varepsilon_{FE}(E'') \cdot dE''$$

- Background radiation spectrum model:

$$B = B(\text{continuum}) + B(\text{discrete})$$

$$B(\text{continuum}) \propto \int_{\Delta N} \varepsilon_{FE}(E) \frac{dE}{E}$$

$$B(\text{discrete}) \propto \sum_i \frac{I_i}{\varepsilon_{FE}(E_i)} \int_{\Delta N} g(E, E_i) dE$$

Spectrum modeling: real example

Facility: nuclear research reactor WWR-10M, INR, Kyiv, Ukraine.

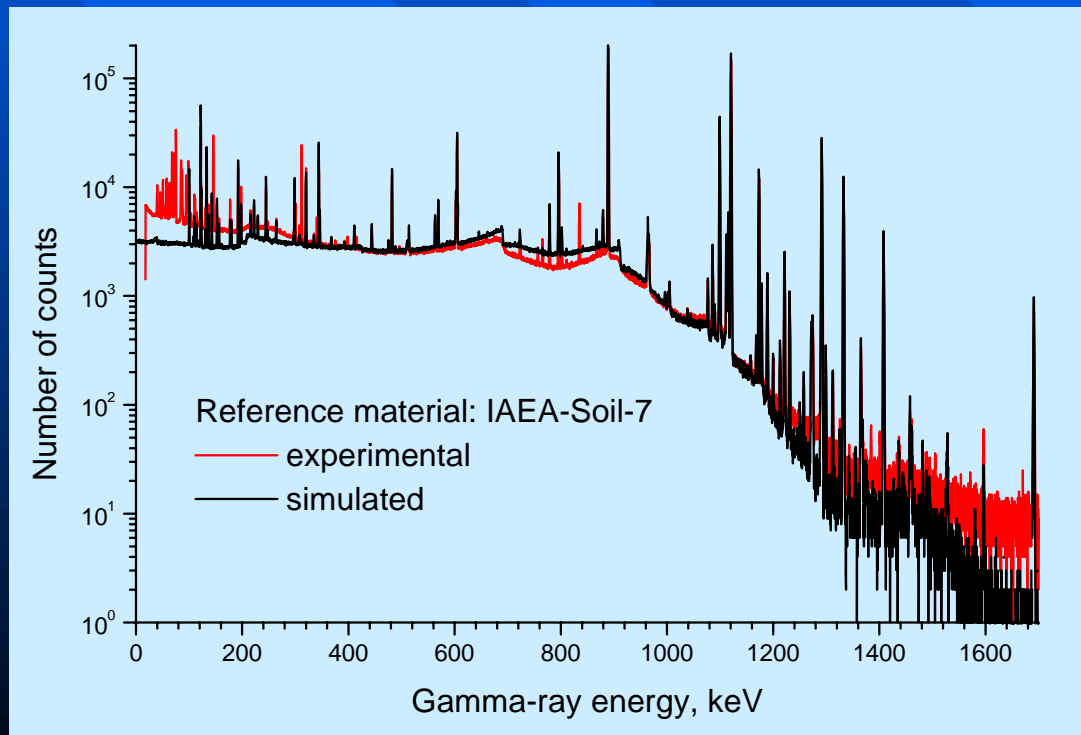
Reference material: soil - IAEA-Soil-7 (m=25 mg).

Irradiation modes: irradiation - 170 h, cooling – 59 days, measurement – 10000 s.

Neutrons: thermal - $1.7 \cdot 10^{13} \text{ cm}^{-2}\text{s}^{-1}$; epithermal - $1.3 \cdot 10^{12} \text{ cm}^{-2}\text{s}^{-1}$; fission - $3.4 \cdot 10^{12} \text{ cm}^{-2}\text{s}^{-1}$.

Detector: coaxial HPGe with 61.8% rel. eff., FWHM < 1.9 keV at 1332.5 keV ^{60}Co .

Electronics: DSP9660, LFC599, and AIM556 (Canberra).



NAAPRO GUI: Sample properties tab

Neutron Activation Analysis Prognosis Code D:\NAAPRO\IAEASL1-1.npr

File Settings About

Sample properties Flux and Time properties Detector and geometry Prognosis

1-H 2-He
3-Li 4-Be 5-B 6-C 7-N 8-O 9-F 10-Ne
11-Na 12-Mg 13-Al 14-Si 15-P 16-S 17-Cl 18-Ar
19-K 20-Ca **21-Sc** **22-Ti** **23-V** **24-Cr** **25-Mn** **26-Fe** **27-Co** **28-Ni**
29-Cu **30-Zn** **31-Ga** 32-Ge **33-As** **34-Se** 35-Br 36-Kr
37-Rb **38-Sr** 39-Y 40-Zr 41-Nb 42-Mo 43-Tc 44-Ru 45-Rh 46-Pd
47-Ag **48-Cd** 49-In 50-Sn **51-Sb** 52-Te 53-I 54-Xe
55-Cs **56-Ba** **57-La** **72-Hf** **73-Ta** 74-W 75-Re 76-Os 77-Ir 78-Pt
79-Au **80-Hg** 81-Tl **82-Pb** 83-Bi 84-Po 85-At 86-Rn
87-Fr 88-Ra 89-Ac
58-Ce 59-Pr 60-Nd 61-Pm **62-Sm** **63-Eu** 64-Gd **65-Tb** **66-Dy** 67-Ho 68-Er 69-Tm **70-Yb** **71-Lu**
90-Th 91-Pa **92-U** 93-Np 94-Pu 95-Am 96-Cm 97-Bk 98-Cf 99-Es 100-Fm

Sample mass
926
Mass units
milligram

Blue Bold text - target element
Red Bold Text - matrix element

RNAA
Clear All

Tin, Z = 50, M = 118.690

Isotope	Abundance, %
Sn-112	0.960
Sn-114	0.660
Sn-115	0.350
Sn-116	14.300
Sn-117	7.610
Sn-118	24.030
Sn-119	8.580
Sn-120	32.850
Sn-122	4.720
Sn-124	5.940

☐ Natural
Content 1e+06 ppm (g/ton)
☒ Target element

Insert Remove Cancel

Decontamination factors

Reset All

Z	Element name	Decontamination factor
31	Gallium	1.00
32	Germanium	1.00
33	Arsenic	1.00
34	Selenium	1.00
35	Bromine	1.00
36	Krypton	1.00
37	Rubidium	1.00
38	Strontium	1000
39	Yttrium	1.00
40	Zirconium	1.00
41	Niobium	1.00
42	Molybdenum	1.00
43	Tecnecium	1.00
44	Ruthenium	1.00
45	Rhodium	1.00
46	Palladium	1.00
47	Silver	1.00
48	Cadmium	1.00
49	Indium	1.00
50	Tin	1.00

OK Cancel

NAAPRO GUI: Flux and Time properties tab

Cd ratio evaluation

Reaction:

Cd cover thickness: cm

Cadmium ratio:

Moderator

Moderator:

T moderator: Kelvin

Neutron Activation Analysis Prognosis Code

File Settings About

Sample properties **Flux and Time properties** Detector and geometry Prognosis

Neutron Spectrum

Thermal neutrons
Flux: 1 / (cm² sec)
Teffective: Kelvin

Epithermal neutrons
Flux: 1 / (cm² sec)

Fast neutrons
☐ Account fast neutrons reactions
Flux: 1 / (cm² sec)
Spectrum:

Cadmium shielding
☐ Epicadmium irradiation
Cadmium cover thickness: cm

Dates and Times

Date Time

Irradiation start:

Cooling start:

Measurement start:

Intervals

Value Units

Irradiation:

Cooling:

Measurement:

Neutron flux per unit lethargy

Date, time, intervals, flux settings

NAAPRO GUI: Detector and Geometry tab

Additional Layers

Add new layer

Z	Symb	Density, g / cm ³	Thickness, cm	Delete
82	Pb	11.3	0.5	<input type="checkbox"/>

Accept Delete Marked Delete All Cancel

Background Lines Intensities

Count Rate, cps

Continuum	10
185.7 keV U-235	0.01
238.6 keV Th-232 (Pb-212)	0.168211
511 keV Annihilation peak	0.10288
609.3 keV Ra-226 (Bi-214)	0.11486
661.6 keV Cs-137	0.0193
1332.5 keV Co-60	0.01
1460.8 keV K-40	0.49774

Accept Cancel

Neutron Activation Analysis Prognosis Code D:\NAAPRO\IAEASL1-1.npr

File Settings About

Sample properties Flux and Time properties **Detector and geometry** Prognosis

Crystal
Matter: Ge Diameter: 7.4 cm
Crystal to End Cap: 0.5 cm Height: 5.3 cm

Source
Geometry: Point Diameter: cm
To Detector: 17 cm Height: cm

Absorbers
Inactive Layer Thickness: 0.07 cm
Input Window Matter: Al
Input Window Thickness: 0.15 cm

Additional Layers N Layers: 0

Background Background Intensities

Detector response
Backscatter Peak Factor: 1
Show for Isotope / Energy: Cs-137

ADC and FWHM
Conversion Gain: 0.32 keV / ch
Number of Channels: 8192
FWHM(keV) = $a0 + a1 \cdot \sqrt{E(\text{keV})}$
a0: 0.36588 a1: 0.039287
Calculate FWHM dependence

Absolute efficiencies
Redraw: All Efficiency Background Response
Log plot of efficiency vs energy (keV). Curves: Total (black), Photo (blue), SE (red), DE (green).

Background spectrum (cps)
Plot of background spectrum (cps) vs energy (keV).

Detector response, relative units
Plot of detector response (relative units) vs energy (keV).

Spectrometer and geometry settings

NAAPRO GUI: Prognosis tab

Neutron Activation Analysis Prognosis Code D:\NAAPRO\IAEASL1-1.npr

File Settings About

Sample properties Flux and Time properties Detector and geometry Prognosis

Make ☒ Reset Report

Output controls:

Rate units: Dose Rh/h Decay Bq Count cps

Elements: Matrix Co Target Ba

Activation products: Matrix Co-60 Target Ba-137m1

Percent of total rates Dose at 10 cm

Show:

- ☒ Dose, count and decay rates
- ☐ Gamma-rays
- ☐ Activation products
- ☐ Spectrum

Dose, count and decay rates

	Matrix	Target	Total
Dose rates			
Irradiation end	3.903e-09	8.771e-08	5.620e-03
Measurement start	4.317e-09	2.906e-08	4.746e-03
Measurement end	4.695e-09	7.474e-09	4.381e-03
Decay rates			
Irradiation end	1.115e+00	9.407e+01	3.967e+06
Measurement start	1.233e+00	3.117e+01	2.336e+06
Measurement end	1.341e+00	8.016e+00	2.086e+06
Count rates			
Measurement start	2.730e-02	3.335e-01	3.201e+04
Measurement end	2.970e-02	8.576e-02	2.996e+04

Viewing calculated Dose, Activity, Count rates

Neutron Activation Analysis Prognosis Code D:\NAAPRO\IAEASL1-1.npr

File Settings About

Sample properties Flux and Time properties Detector and geometry Prognosis

Make ☒ Reset Report

Output controls:

Target element(s) All

Performance Index Detection limit Units ppm

Thresholds:

Energy, keV 25

Total gamma-rays 1

Performance 10

Precision, % 100

Gamma-rays

Energy, keV	Attribution	Total gammas	Gammas per sec	Performance	Precision, %
479.622	Dy-165	1.005e+04	3.349e+01	Not defined	Not defined
486.522	Ba-131	5.726e+00	1.909e-02	Not defined	Not defined
487.021	Cu-64 Annh. (94.13%) + Eu-152m1 Annh. (5.85%) + Zn-65 Annh. (0.02%) + ...	6.812e+04	2.271e+02	Not defined	Not defined
496.326		1.476e+02	4.919e-01	Not defined	Not defined
498.400		9.972e+01	3.324e-01	Not defined	Not defined
511.000	Cu-64 Annh. (94.13%) + Eu-152m1 Annh. (5.85%) + Zn-65 Annh. (0.02%) + ...	1.049e+00	3.498e-03	Not defined	Not defined
515.467	Dy-165m1 (90.72%) + Dy-165 (9.28%)	9.363e+04	3.121e+02	Not defined	Not defined
522.540	Sm-155	5.157e+02	1.719e+00	Not defined	Not defined
531.400	Sm-153	8.342e+01	2.781e-01	Not defined	Not defined
540.516	Dy-165	1.285e+03	4.282e+00	Not defined	Not defined
545.834	Dy-165	3.701e+04	1.234e+02	Not defined	Not defined
559.100	As-76	4.938e+04	1.646e+02	Not defined	Not defined
563.230	As-76	1.318e+03	4.395e+00	Not defined	Not defined
564.240	Sb-122	7.453e+02	2.484e+00	Not defined	Not defined

Viewing gamma-rays for target elements activation products

NAAPRO GUI: Prognosis tab

Neutron Activation Analysis Prognosis Code D:\NAAPRO\IAEASL1-1.npr

File Settings About

Sample properties Flux and Time properties Detector and geometry Prognosis

Make ☒ Reset Report

Show

- ☐ Dose, count and decay rates
- ☐ Gamma-rays
- ☒ Activation products
- ☐ Spectrum

Output controls

Activity on in

Thresholds

☒ Total Activity

Activation products

Activation product	Attribution	Chain(s)	Gamma ray	Total activity
Fe-55 (2.73513 y)	Fe	Fe-54(n,g)Fe-55	5.899	3.941e-05
Fe-59 (44.503 d)	Fe	Fe-58(n,g)Fe-59	1099.251	2.731e-05
K-42 (12.36 h)	K	K-41(n,g)K-42	1524.600	1.753e-02
La	La	La-139(n,g)La-140	1596.210	4.993e-04
Mn	Mn	Mn-55(n,g)Mn-56	846.754	1.824e+00
Na	Na	Na-23(n,g)Na-24m1(IT)Na-24(75.46%)+Na-23(n,g)Na-24(24.54%)	1368.633	1.551e-02
Sb	Sb	Sb-123(n,g)Sb-124m2(IT)Sb-124m1(58.98%)+Sb-123(n,g)Sb-124m1(41.02%)	564.240	3.515e-06
Sc	Sc	Sc-45(n,g)Sc-46(63.97%)+Sc-45(n,g)Sc-46m1(IT)Sc-46(36.03%)	61.413	4.938e-06
Sm	Sm	Sm-152(n,g)Sm-153	602.720	1.898e-06
Sm	Sm	Sm-154(n,g)Sm-155	41.542	3.112e-05
Ti	Ti	Ti-50(n,g)Ti-51	142.528	1.181e-05
V	V	V-51(n,g)V-52	41.542	4.446e-04
			104.320	1.244e-03
			320.076	1.459e-02
			1434.060	1.945e-01

Neutron Activation Analysis Prognosis Code D:\NAAPRO\IAEASL1-1.npr

File Settings About

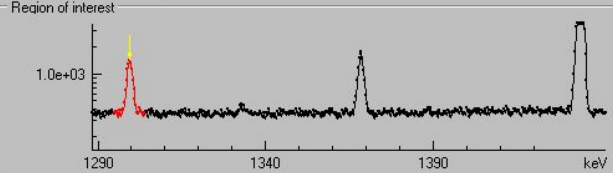
Sample properties Flux and Time properties Detector and geometry Prognosis

Make ☒ Reset Report

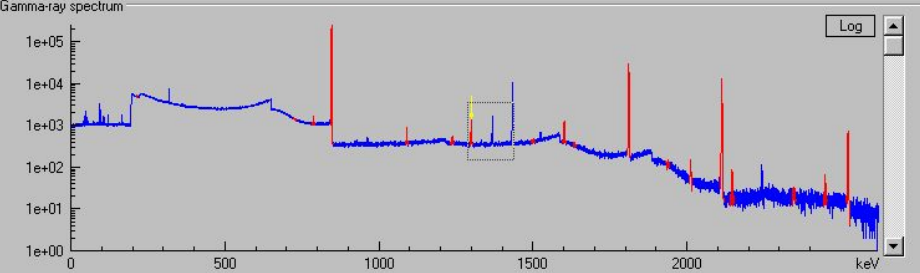
Show

- ☐ Dose, count and decay rates
- ☐ Gamma-rays
- ☒ Activation products
- ☐ Spectrum

Region of interest



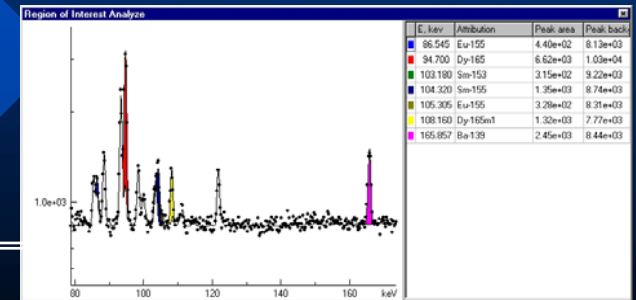
Gamma-ray spectrum



Marker Channel: 4061 Energy: 1299.680 Counts: 1381 Nuclide: Mn-56(1810.720 SE) + Sm-155(1301.200)

Spectrum Grid X Grid Y Total counts: 9.30372e+06 Show peaks of Mn-56

ROI: Point size Line Off Boundaries: 4026 - 4505 (1288.32 - 1441.60 keV) Counts: 249417 Analyze



Thank you for your attention.